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Performance Evaluation of a Four-Legged Signalized Intersection with Variable Traffic Flow Dynamics

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Abstract: The rapid growth of population and vehicular traffic has necessitated effective urban planning strategies to mitigate traffic congestion and enhance roadway efficiency. This study focuses on a critical signalized intersection in Konya, Turkiye's largest metropolitan area, which is notable for its agricultural, industrial, and educational significance. Strategically positioned at the nexus of major transportation routes linking the Black Sea and Central Anatolia regions to the Mediterranean and Aegean areas, Konya exhibits considerable logistical potential. The Coşandere intersection, located in the Selçuklu district, was selected for analysis due to its four-legged configuration, featuring three lanes on both the south and north approaches and two lanes on the east and west approaches. Additionally, suitable turning islands and U-turn pockets are provided on the south and north approaches. Observational data indicate that the evening peak period poses significant operational challenges. A video surveillance system was employed to monitor vehicle movements, yielding a traffic volume of 1,874 vehicles per hour. The existing geometric design, traffic dynamics, and signalization were modelled using PTV Vissim software to assess the intersection's performance. The analysis revealed an average delay of 44.1 seconds per vehicle, an average of 0.9 stops per vehicle, and an average vehicle speed of 29.6 km/h, resulting in a Level of Service (LOS) classification of D. These findings indicate that the intersection currently accommodates traffic demand to a moderate degree. However, substantial improvements in operational efficiency could be achieved through enhancements to the signalization system, including the potential implementation of an adaptive traffic signal control system. This study provides valuable insights for traffic management authorities and urban planners aiming to optimise intersection performance in rapidly developing urban environments.

Keywords: Delay; Intersection; Level of service (LOS); Number of stops; Vehicle speed

1 Introduction

Compared to developed countries, there is a rapid migration trend from rural to urban areas in underdeveloped and developing countries searching for better education and health facilities or more attractive job opportunities. In addition, the number of people living in urban centers is increasing yearly. Population growth can lead to constraints if facilities and resources do not grow simultaneously. As a result of developing technology and easier access to facilities, the use of private vehicles is increasing in cities without an effective public transport system. There has been a significant increase in vehicle ownership and use in recent years, in parallel with global population growth [1]. In addition, the COVID-19 pandemic has also had an increasing impact on people's individual car use due to social isolation and the risk of transmission [2]. Although the pandemic is behind us, changing transport habits is not easy. Increasing the number of vehicles on the road benefits users but also disadvantages local administrations and transport systems. As vehicles increase, so do road accidents, air and noise pollution, and congestion, especially on urban roads. This situation makes traffic management difficult, disrupts urban life, and decreases people's satisfaction with urban systems. In addition, intersections with operational and safety issues are thought to cause drivers to crash due to excitement, panic, etc. in the face of complexity [3–7]. For these reasons, there is a need for effective planning. However, in developing countries like Türkiye, unplanned, irregular, and dysfunctional roads can be built during the planning and construction stages of roads due to both the lack of knowledge and inexperience of planners and the political behaviour of decision-makers [8].

Intersections are common areas where traffic flows from two or more directions intersect, separate, and merge. Similarly, intersections are defined as those sections of road where traffic flows from different directions move in an orderly fashion and use each other according to the rules defined in the standards [9]. In another definition, intersections are the places where motorised and non-motorised vehicles and pedestrians meet [10]. Intersections stand out as areas where traffic flow chaos and accidents occur intensively. For this reason, the need for effective planning of intersections is always a priority area for planners. Intersections can be classified as level intersections and different level intersections depending on the intersection status of the approach arms [11]. Road sections shared by traffic streams moving in different directions and controlled by traffic signs without traffic lights are called unmanned intersections [12]. In controlled intersections where signaling systems are used, the order and sequence of vehicles passing through the intersection are planned by signaling systems [13]. Signaling systems increase road safety by eliminating the crossing of traffic flows in different directions within the intersection [14]. It is essential to determine the correct type of intersection and control conditions for intersections depending on the geometric constraints and traffic type. In addition, signaling arrangements should help keep intersection performance high. Although it is tough to design an uninterrupted transport infrastructure that can respond to the increasing transport demand due to the growing number of vehicles, it will be possible with the right design approaches. Several performance parameters are considered during the inspection, evaluation, and planning stages at intersections. These are delay time per vehicle, number of stops per vehicle, average speed, which can be obtained directly from the field, and service level parameters that can be determined from this data. Delay is defined as the time vehicles can pass through the intersection without slowing or stopping in the absence of congestion or control systems and the time that vehicles can pass through the same area when slowing or stopping due to congestion or control systems. In general, the delay is measured in seconds. It is reported as vehicle delay time for a vehicle or as delay per vehicle, which is the average of all vehicles in the area. The delay per vehicle as a zone average is a key performance indicator for interpreting an intersection's traffic density and operational status.

Vehicles may come to a complete stop at 0 km/h for various reasons, including signaling and traffic density. The number of stops per vehicle indicates the number of times vehicles stop on the road sections where traffic flow is analyzed. This value can be determined regionally or for a specific period. This value is usually given as an average on a section of road or at an intersection and not on a vehicle-by-vehicle basis. A high value indicates that the traffic flow is constantly interrupted and is stop-and-go. It also shows congestion. Frequent stops mean that vehicles are continually accelerating and braking. This leads to a rapid increase in fuel consumption and exhaust emissions. Another performance parameter is average speed. Average speed can be calculated on a particular road or lane for different types of vehicles or at intersections. It is usually expressed in kilometers per hour (km/h). This value is usually given as an average for the lane, vehicle type, region, or intersection in question rather than on a vehicle-by-vehicle basis. Low average speeds usually indicate traffic jams and congestion. Heavy traffic congestion or lane-changing activities that cause hesitation may reduce the average speed. A high average speed suggests that the effect of environmental factors that may impede or restrict traffic flow is low and that vehicles are moving more smoothly. Although high average speeds indicate that the performance of the intersection is high, it would be healthier to comment within the legal speed limits. In addition to the performance parameters that can be obtained directly from the field, the LOS in which the road is categorized according to these performance parameters is also critical. The LOS concept is classified into six classes from A to F, where A is the best traffic flow condition and F is the worst [15]. These parameters are used as an average indicator of average speed, delay, travel time, operating conditions, and road safety in the traffic flow.

The study of performance parameters and the variables influencing performance parameters and their improvement has been exciting for researchers. In one study, the variables affecting control delay, one of the performance parameters at signaled intersections, were investigated, and the concept of average control delay was defined [16]. Signal duration and geometric arrangements are also frequently studied in the literature. In the reviewed studies, a system has been developed that dynamically responds to the traffic density at intersections and optimizes the signal duration [17]. In addition, improvements in performance parameters such as vehicle delay times, LOS, and fuel consumption were achieved by adjusting the existing signal durations using the optimization technique [18]. Another study proposed optimal intersection arrangements based on parameters such as queue length, speed, and travel time [19]. The objective of these studies is common. They aim to allow traffic to flow without stopping, at higher speeds within legal limits, and with low delay values. In this direction, it is stated that adaptive traffic management systems can improve the current situation in issues such as reducing fuel consumption, reducing environmental pollution and noise, reducing traffic accidents, and minimizing time spent in traffic [20].

As a developing country, Turkey is experiencing rapid growth in population and vehicle numbers, especially in urban centers. Local authorities and the Ministry of Transport and Infrastructure are conducting intensive research and practices to improve transport systems. The success of these studies depends on a good analysis of the current situation. The studies generally focus on the main arteries. However, various traffic problems are also observed on the collector and distributor roads for the main arteries. This study aims to analyze the current situation at an intersection that plays a collector and distributor role for main arterials. By analyzing the current situation of an intersection with these characteristics and raising the operating standards to eliminate any problems, the main arteries' performance will be improved. In addition, the study will reflect the regional traffic culture and serve as a reference for city- and country-wide studies.

2 Material and Methods

2.1 Determination of Study Site

Konya province is the largest city in Türkiye by area. It is also located on the roads connecting the Black Sea and Central Anatolia regions with the Mediterranean and the Aegean region with the eastern provinces. It is one of the leading cities in industry, agriculture, and animal husbandry and has important logistical mobility with rail, air, and road transport alternatives. Konya is home to five universities: Selçuk University, Necmettin Erbakan University, Konya Technical University, KTO Karatay University, and Konya Food and Agriculture University. Konya is also home to relevant units of many official institutions. With these aspects in mind, Konya is highly active in human mobility and vehicular traffic. Although the effect of the hilly terrain is not very obvious in road construction and traffic planning in Konya, which is spread over a vast plain, managing the intense pedestrian and vehicle traffic requires good planning. At the same time, bicycle traffic is also essential in Konya, which has the longest bicycle path in Türkiye at 595 kilometers [21]. In addition to vehicle traffic, intensive pedestrian and bicycle traffic also highlights the need for effective planning at intersections where different types of traffic intersect. The province of Konya was selected as a pilot province for the study due to its geopolitical location, especially the flatness of the city center and the high mobility of pedestrians and vehicles. The districts of Meram, Karatay, and Selçuklu in the center of Konya were selected as pilot districts due to the presence of a bus station, airport, universities, organized industry, and high mobility (Figure 1).

Figure 1. Location of the specified province and district

Figure 2. Coşandere intersection view

The study aimed to identify an intersection that is uniform, controlled by a signaling system, has no obvious geometric problems, has vehicle mobility at all hours of the day, and acts as a collector and distributor for the main arteries. For this purpose, many intersections in the Selçuklu district were analyzed, considering the number of legs, geometry, lanes, control systems, and vehicle mobility potential. Among the options, one intersection was identified where the number of lanes on the entry and exit legs is compatible, there is no obstacle to data collection in the vicinity, and the lane lines are clear. The intersection where the study will be conducted is a four-leg signalized intersection located at the junction of Coşandere and Veysel Karani streets in the Kosova neighborhood, Selçuklu district, Konya province (Figure 2). The intersection will be named Coşandere, one of the intersecting streets better known in the neighborhood.

The Coşandere intersection is very close to Selçuk University, and the neighborhood has a dense settlement and mobility. The intersection is located at the junction of several intercity roads. This situation has an increasing impact on vehicle traffic. The Coşandere intersection is named based on the directions of the approach legs, as shown in Figure 3. The south and north approach legs have left turn lanes and are three lanes. The east and west approach legs have two lanes; on the west approach leg, one lane before the intersection is dedicated directly to the right turn pocket. Right-turn islands are also on all four legs, and U-turn pockets are on the south and north approach legs.

Figure 3. Intersection location and name of intersection legs

2.2 Intersection Traffic Data Obtain

Field observations were conducted to obtain traffic data for the Coşandere intersection under study. During the field studies, it was observed that the traffic volume values for the Coşandere intersection do not vary much on different days. The evening volume is higher than the morning peak volume and is worthy of investigation. During midday, the number of vehicles is deficient compared to the evening or morning peak hours. One of the main problems encountered in the data collection phase of traffic engineering field studies is the complete determination of the movement of all vehicles in the study area. A video filming device (Figure 4) was used that allows wide-angle shots from a high point [22].

Figure 4. Used video recording system [22]

While the evening peak hour was anticipated to exhibit higher traffic volumes based on field studies, obtaining morning peak hour values for comparative analysis was also deemed desirable. The midday peak hour was not included in the study due to its significantly lower traffic levels. Video recordings were captured from 07:45 to 08:45 in the morning and from 17:30 to 18:30 in the evening over three different days in May 2024. The collected footage was analyzed using counting software, allowing for the extraction of relevant data for the study.

3 Findings

Field observations were conducted to analyze the Coşandere intersection's signaling system. Although the left turn phase in the existing signaling system at the intersection is designed separately for the north and south legs, all directions for the relevant leg operate simultaneously and jointly. In addition, there is a standard red time of two seconds between the signals of different directions for safety reasons. Observations have shown that the cycle time is 124 seconds. Small human errors may occur in field observations. For this reason, the sketch of the signal plan obtained from Konya Metropolitan Municipality is shown in Figure 5, and the signal program, including phase times, is shown in Figure 6.

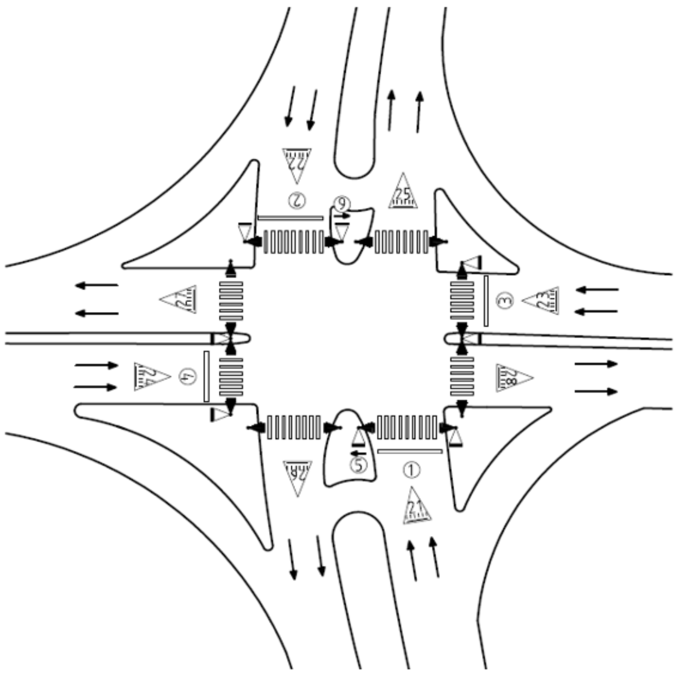

Figure 5. Signal plan of signalized intersection

Figure 6. Examined traffic signal program

The field observations show that, although the left-turn phase at the intersection is designed separately for the north and south legs, all leg directions work together simultaneously. For this reason, the phase arrangement at the intersection consists of four separate groups for four legs. In step 1, there is a 40-second green time for the south leg (all directions). Then, the signal is green for the west leg, and the green time is 20 seconds. In the third stage of the signaling program, there is a green time of 27 seconds for all directions in the north leg, as in the south leg. In the final stage, the signal is green for 13 seconds for the east leg, which has a shorter green time than the other branches. Although included in the signal plan sketch, the signals defined for pedestrians are not included in the study, as they do not affect the performance parameters.

In line with the investigations, it was found that the evening peak hour values are higher than the morning peak hour values. For this reason, it was decided to consider the evening peak hour values. The data obtained are shown in Table 1. As a result of the observations made for the Coşandere intersection, the number of vehicles passing through the intersection in one hour was found to be 1874 vehicles. By converting the maximum values obtained from period-based observations to hourly values, the intersection volume was found to be 1984 vehicles/hour. The difference between the two calculated values is quite natural and reflects the change in traffic throughout the periods. However, it is expected that sometimes effects such as traffic at the previous intersection, illegal parking on the roadside, meteorological conditions, or driver psychology can cause instantaneous differences and deviate from the actual values at the intersection. For this reason, the study used the hourly volume value of 1874 vehicles/hour obtained directly from the vehicle counts for the analysis.

Table 1. Intersection traffic data

		Car and Minibus (vehicle/hour)			**Heavy Vehicle [Bus, Truck and Lorry] (vehicle/hour)**			**Average Number of Vehicles (for three days)**		
		1st day	2nd day	3rd day	1st day	2nd day	3rd day	Car and Minibus	Heavy Vehicle	Average Total
South	Period 1	98	94	90	3	3	1	94	2	96
	Period 2	99	96	88	3	1	3	94	2	97
	Period 3	103	101	108	2	2	2	104	2	106
	Period 4	109	99	95	1	4	0	101	2	103
	Total (Σ)	409	390	381	9	10	6	394	8	402
North	Period 1	121	107	126	4	2	5	118	4	122
	Period 2	152	161	146	2	3	3	153	3	156
	Period 3	163	135	163	3	2	2	154	2	156
	Period 4	159	163	151	2	4	4	158	3	161
	Total (Σ)	595	566	586	11	11	14	582	12	594
East	Period 1	48	45	53	2	2	3	49	2	51
	Period 2	49	47	48	1	3	3	48	2	50
	Period 3	57	63	59	2	2	3	60	2	62
	Period 4	58	60	65	3	1	2	61	2	63
	Total (Σ)	212	215	225	8	8	11	217	9	226
West	Period 1	151	153	145	4	5	3	150	4	154
	Period 2	163	156	165	6	3	3	161	4	165
	Period 3	161	163	163	3	4	4	162	4	166
	Period 4	154	166	170	3	4	2	163	3	166
	Total (Σ)	629	638	643	16	16	12	637	15	652
Coşandere Intersection	Average Total (Σ)	1845	1809	1835	44	45	43	1830	44	1874

The direction in which vehicles exit the intersection is also an important consideration, as it affects the average speed, delay, and number of stops at the intersection and, therefore, the LOS. Depending on the type of turn vehicles make according to their exit direction, there may be geometric arrangements (turn pockets and turn islands) and differences in signaling systems (left turns are given differently from the main flow) at the intersection. For this reason, in addition to the number of vehicles in the entry section, the exit direction of the existing cars was also analyzed. The study identified four types of movement to determine the exit direction. Movement Type 1 refers to the right turn. Movement Type 2 is the situation where the vehicles continue straight ahead. Movement Type 3 is the left turn, and movement Type 4 is the U-turn. Figure 7 shows the movement types of the directions.

The distribution of the current vehicles at the intersection according to the determined intersection movement types is given in Table 2. When the northern leg is examined, it is seen that the movements are concentrated as right turns and straight ahead. The reason for the high correct turn rate compared to the other legs is that Istanbul Street, in the relevant direction, connects Konya with the metropolitan cities of Izmir and Istanbul. For the eastern leg, straight ahead (towards Istanbul Street) is relatively high compared to other movement types. The western leg is the direction coming from the mentioned main artery. It is seen that the vehicles coming from this direction mostly exhibit the left turn movement, which is the number 3 movement type. With this route, the vehicles leaving the main flow head toward the center of the Kosovo Street neighborhood, with dense commercial areas and settlements. When the movement types are examined for the south, which is the four legs at the intersection, it is seen that the number 2 straight ahead and the number 3 left turn movement are mostly preferred. These directions are Istanbul Street and the Kosovo Street neighborhood. Although there are different movement types, the movement directions are generally similar.

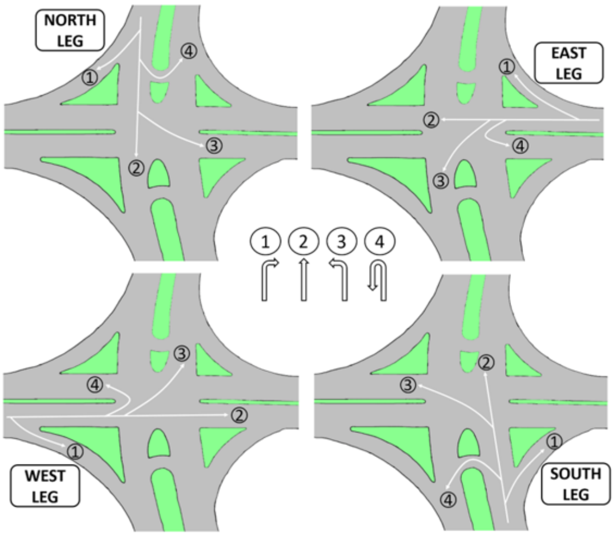

Figure 7. Movement types

Table 2. Vehicle distributions according to movement types

Legs	Movement Types			
	Type 1 (%)	Type 2 (%)	Type 3 (%)	Type 4 (%)
North Leg	0.32	0.54	0.11	0.03
East Leg	0.17	0.68	0.13	0.02
West Leg	0.07	0.20	0.72	0.01
South Leg	0.01	0.42	0.55	0.02

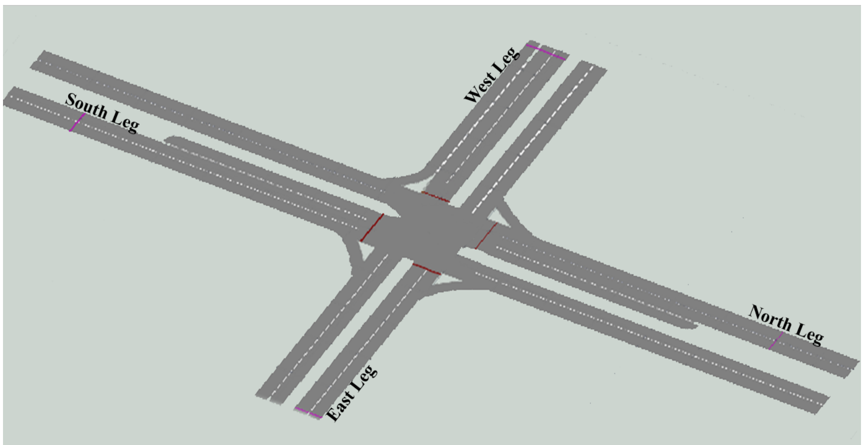

Figure 8. Intersection modeling

Table 3. Intersection performance indicators

Performance Indicators	Value
Average delay per vehicle (s)	44.1
Average number of stops per vehicle	0.9
Average vehicle speed (km/h)	29.6
LOS	D

The aim of this study is to determine the performance parameters of the examined intersection based on the obtained data. PTV Vissim software, one of the traffic micro-simulation programs, was used for this study. Intersection geometric modeling was performed in the PTV Vissim program. After the placement of road layers, the volume values of different types of vehicles and the routes they will follow were defined in the system. A signal program was defined to provide intersection management, and signal positions were placed on the road. At this stage, unlike the existing signal program, left turns were not created separately since they sound the same as the main direction in the south and north legs, and the entire intersection was modeled in 4 phases based on legs (Figure 8). The desired parameters were defined, and the outputs obtained by running the program are presented in Table 3.

Sometimes, the values obtained in analysis programs may show slight differences from the real situation. The main reason for this situation is that environmental effects and driver psychology cannot be reflected in the program, as in the real situation. The results of the analysis studies were compared with the real situation. Since there were no obvious differences from the observations, there was no need to apply the calibration process.

4 Results and Discussion

Within the scope of the study, Konya province was selected as a pilot province due to its geopolitical location, especially the flat spread of the city center, and high pedestrian and vehicle mobility. Konya is the largest city in Türkiye in terms of surface area. It also has intense vehicle mobility, located on the roads connecting the Black Sea and Central Anatolia regions to the Mediterranean and the Aegean region to the eastern provinces. Hosting five different universities, Konya also hosts significant logistics mobility with its railway, airway, and highway transportation alternatives. Selçuklu district was selected as a pilot province because it hosts bus terminals, airports, universities, organized industries, and intense mobility. Many intersections in the Selçuklu district were examined by considering the number of legs, geometry, lane numbers, control systems, and vehicle mobility potential criteria. Among the different options, a 4-legged signalized intersection was determined at the intersection of Coşandere and Veysel Karani streets in the Kosova neighborhood, where the number of lanes is compatible at the entrance and exit legs, there is no obstacle to data collection around it, and the lane lines are clear. The intersection is named Coşandere, one of the streets on which it intersects, and is more commonly known among the public.

The four legs at the Coşandere intersection are named according to their directions. Field observations and preliminary counts determined that the evening peak hour values were higher than the morning peak hour values. For this reason, it was decided to consider the evening peak hour values. After the data collection and digitization, the intersection volume value was 1874 vehicles/hour (Table 4).

Table 4. Number of vehicles

	Number of Vehicles		
	Car and Minibus	Heavy Vehicle	Total
South Leg	394	8	402
North Leg	582	12	594
East Leg	217	9	226
West Leg	637	15	652
Intersection (Total)	1830	44	1874

In addition to the volume values obtained, the movement types of the vehicles were also examined. The right turn was grouped as movement number 1, the situation where the vehicles continue straight was grouped as movement number 2, the left turn was grouped as movement number 3, and the U-turn was grouped as movement type number 4. Considering that the factor determining the movements of the vehicles is the exit direction, the examinations determined that the directions of Yeni İstanbul Street and Bosnia Hersek neighborhood were the most frequently used. Based on this situation, it was seen that there were differences in the movement types for all legs and that it was not possible to generalize. In the signaling plan, the plan should consider the turn distributions, i.e., movement types.

To analyze the signaling system of the Coşandere intersection examined within the scope of the study, field observations were made. At the same time, the signal program, including the signal plan sketch and phase durations, was obtained from Konya Metropolitan Municipality. When the signal program was examined, as determined in the field observations, although the left turn phase was designed separately for the north and south legs at the intersection, all directions worked together for the entire leg. The fact that the left-turn phase does not work separately revealed unnecessary details regarding the planning stages and labor expenditure. In addition, the details of the signal program make it difficult to understand. For this reason, left turn phases should be planned without separating from the main flow. It is thought that the green period determined for all legs is approximately proportional to the leg volumes, and there are no apparent problems with the intersection operation. However, examples have been observed where vehicles tend to pass without stopping when the signaling changes from green to yellow. For this reason, increasing the protection periods or installing electronic red light violation detection systems to prevent possible accidents may be considered in the coming years.

PTV Vissim traffic micro-simulation software was used to determine the performance parameters of the intersection examined by the obtained data. The intersection performance indicators were obtained by defining the program's field geometry, traffic data, and signaling system. The average delay per vehicle was obtained as 44.1 seconds. Although this value is lower during the day, it is pretty long for drivers in the evening peak hours. Drivers may exhibit stress and a tense driving profile due to increased delay times. Delay times can be reduced with geometric improvements made at the intersection, arrangements in the signaling system, or even by using adaptive signaling systems at the intersection. The average number of stops per vehicle was found to be 0.9. Although the number per vehicle is not very high, when the high vehicle volume of the intersection is considered, it is seen that it is a number that spreads over the whole and stops the traffic flow quite a lot. This value can also be reduced with improvements at the intersection. The average vehicle speed value is another intersection performance indicator obtained from the PTV Vissim program. It was determined that the average vehicle speed value in the examination area was 29.6 km/h. Although there are different speed limits along the street for the intersection approach legs, the legal speed limit in the intersection area is determined as 50 km/h. Although the average vehicle speed value is mathematically lower than the legal speed limit, higher speeds will cause various problems due to the high pedestrian density and vehicle numbers around the intersection. Therefore, the researchers determined this speed value to be an acceptable speed. The LOS value, which can also be considered as the quality of traffic in the region or the satisfaction level of users, was obtained as class D. When the location of the intersection is considered, the service focus, and the benefit-cost perspective, it is thought that the service value for the intersection is acceptable. Still, it can be increased to class C with simple geometric arrangements and improvements in the signaling system. However, higher-level enhancements are not necessary in the current situation. In addition, the results of the analysis studies were compared with those of the actual problem. Since there were no apparent differences between the program outputs and the observation results, there was no need to apply the calibration process.

5 Conclusion

According to field observations, performance analyses, and scientific studies, although the Coşandere intersection in the Selçuklu district is not located on the main artery, it is used much more intensively than in many neighborhood intersections. The main factor affecting this situation is that the intersection serves as a connection point between many vital locations and roads. According to the obtained performance parameters, it is thought that the intersection is not problematic and requires urgent arrangement. Still, improvements can be made, especially regarding the average number of stops per vehicle and average delay per vehicle. The intersection geometry generally does not contain significant problems. However, there are differences between the legs in terms of left-turn lanes and right-turn islands. For example, while there is a separation from the existing lane to the right turn island on the eastern approach leg, a completely separate lane operates for the right turn island on the western approach leg. In addition, if the left turn lanes are separated from further back on the southern and northern legs, improvements can be achieved in the queue number and average number of stops per vehicle values.

When examined in terms of the signaling system, there is a signaling system that can be considered as 4-phase due to fixed-time and left-turn phases being dysfunctional at the intersection. When the leg volumes and green times are examined, it is thought that there is a volume-oriented distribution, but it is not possible to talk about proportionality. Undoubtedly, the right-turn islands present in all branches and the fact that the vehicles using these islands, that is, turning right, are not affected by the signaling system can have an effect that can change all expectations. Indeed, right-turn rates are quite high, especially in the west and south legs. In addition, it is seen in the observations made during the day that there is a density difference between the legs depending on the hours. For this reason, researchers think that the adaptive signaling arrangement for the Coşandere intersection will significantly increase the efficiency of the intersection and is recommended to the local administration.

Author Contributions

The authors have contributed equally to all stages of the preparation of the manuscript and have read and agreed to the published version.

Data Availability

The intersection observation data supporting our research results are included in the article.

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Conflicts of Interest

The authors declare that they have no conflicts of interest.

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